A search for missing baryons with the Sunyaev-Zel’dovich effect

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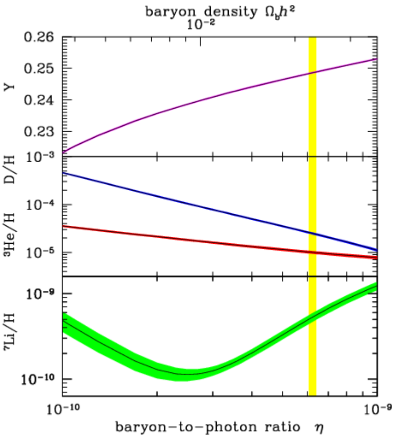
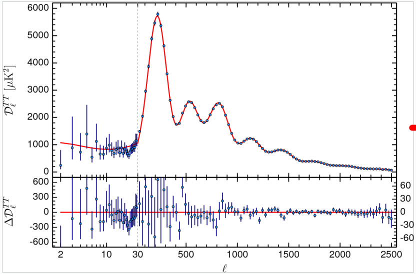
ArXiv:1709.10378
Dubrovnik, October 25, 2018

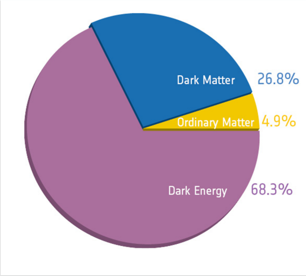
Baryon content



Cyburt et al. 2008

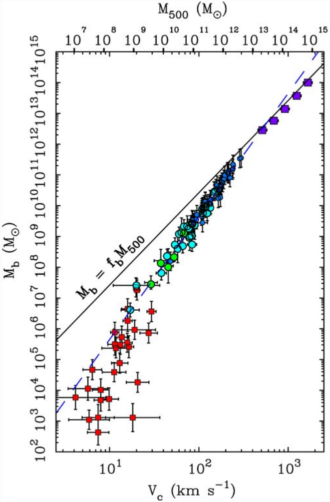
Baryon content





Planck Collaboration 2015 XIII

Baryons at low z



McGaugh et al. 2010

Baryons at low z

TABLE 1
THE COSMIC ENERGY INVENTORY

Category	Parameter		Components[a]	Totals[a]
1	Dark sector:			0.954 ± 0.003
1.1	Dark energy		0.72 ± 0.03	
1.2	Dark matter		0.23 ± 0.03	
1.3	Primeval gravitational waves		$\lesssim 10^{-10}$	
2	Primeval thermal remnants:			0.0010 ± 0.0005
2.1	Electromagnetic radiation		$10^{-4.3 \pm 0.0}$	
2.2	Neutrinos		$10^{-2.9 \pm 0.1}$	
2.3	Prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$	
3	Baryon rest mass:			0.045 ± 0.003
3.1	Warm intergalactic plasma		0.040 ± 0.003	
3.1a	Virialized regions of galaxies	0.024 ± 0.005		
3.1b	Intergalactic	0.016 ± 0.005		
3.2	Intracluster plasma		0.0018 ± 0.0007	
3.3	Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
3.4	Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
3.5	White dwarfs		0.00036 ± 0.00008	
3.6	Neutron stars		0.00005 ± 0.00002	
3.7	Black holes		0.00007 ± 0.00002	
3.8	Substellar objects		0.00014 ± 0.00007	
3.9	H I + He I		0.00062 ± 0.00010	
3.10	Molecular gas		0.00016 ± 0.00006	
3.11	Planets		10^{-6}	
3.12	Condensed matter		$10^{-5.6 \pm 0.3}$	
3.13	Sequestered in massive black holes		$10^{-5.4}(1 + \epsilon_n)$	
4	Primeval gravitational binding energy:			$-10^{-6.1 \pm 0.1}$
4.1	Virialized halos of galaxies		$-10^{-7.2}$	
4.2	Clusters		$-10^{-6.9}$	
4.3	Large-scale structure		$-10^{-6.2}$	
5	Binding energy from dissipative gravitational settling:			$-10^{-4.9}$
5.1	Baryon-dominated parts of galaxies		$-10^{-8.8 \pm 0.3}$	
5.2	Main-sequence stars and substellar objects		$-10^{-8.1}$	
5.3	White dwarfs		$-10^{-7.4}$	
5.4	Neutron stars		$-10^{-5.2}$	
5.5	Stellar mass black holes		$-10^{-4.2}\epsilon_s$	
5.6	Galactic nuclei: early type		$-10^{-5.6}\epsilon_n$	
5.7	Galactic nuclei: late type		$-10^{-5.8}\epsilon_n$	
6	Poststellar nuclear binding energy:			$-10^{-5.2}$
6.1	Main-sequence stars and substellar objects		$-10^{-5.8}$	
6.2	Diffuse material in galaxies		$-10^{-6.5}$	
6.3	White dwarfs		$-10^{-5.6}$	
6.4	Clusters		$-10^{-6.5}$	
6.5	Intergalactic		$-10^{-6.2 \pm 0.5}$	
7	Poststellar radiation:			$10^{-5.7 \pm 0.1}$
7.1	Resolved radio-microwave		$10^{-10.3 \pm 0.3}$	
7.2	FIR		$10^{-6.1}$	
7.3	Optical		$10^{-5.8 \pm 0.2}$	
7.4	X-ray–γ-ray		$10^{-7.9 \pm 0.2}$	
7.5	Gravitational radiation: stellar mass binaries		$10^{-9 \pm 1}$	
7.6	Gravitational radiation: massive black holes		$10^{-7.5 \pm 0.5}$	
8	Stellar neutrinos:			$10^{-5.5}$
8.1	Nuclear burning		$10^{-6.8}$	
8.2	White dwarf formation		$10^{-7.7}$	
8.3	Core collapse		$10^{-5.5}$	
9	Cosmic rays and magnetic fields			$10^{-8.3^{+0.6}_{-0.3}}$
10	Kinetic energy in the IGM			$10^{-8.0 \pm 0.3}$

[a] Based on Hubble parameter $h = 0.7$.

Fukugita & Peebles 2004

- Only 10% of baryons form galaxies
- The gas observed around galaxies (CGM) and in clusters (ICM) can account for another 10% of baryons

THE ASTROPHYSICAL JOURNAL, 514:1–6, 1999 March 20

WHERE ARE THE BARYONS?

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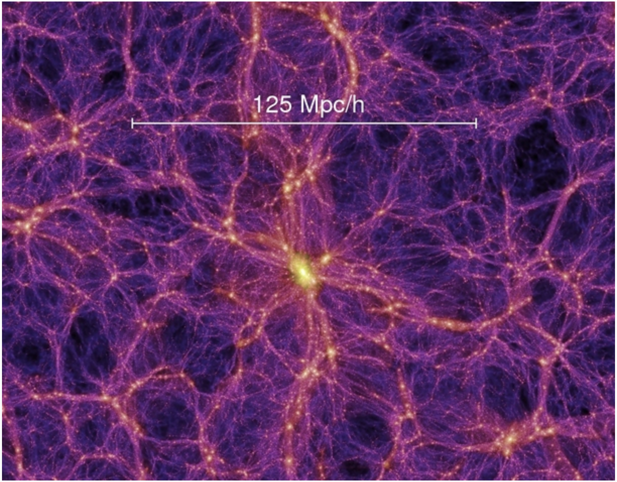
ABSTRACT

New high-resolution, large-scale cosmological hydrodynamic galaxy formation simulations of a standard cold dark matter model (with a cosmological constant) are utilized to predict the distribution of baryons at the present and at moderate redshift. It is found that the average temperature of baryons is an increasing function of time, with most of the baryons at the present time having a temperature in the range of 10^5–10^7 K. Thus not only is the universe dominated by dark matter, but more than one-half of the normal matter is yet to be detected. Detection of this warm/hot gas poses an observational challenge, which requires sensitive EUV and X-ray satellites. Signatures include a soft cosmic X-ray background, apparent warm components in hot clusters due to both intrinsic warm intracluster and intercluster gas projected onto clusters along the line of sight, absorption lines in X-ray and UV quasar spectra [e.g., O VI (1032, 1038) A lines, O VII 574 eV line], strong emission lines (e.g., O VIII 653 eV line), and low-redshift, broad, low column density Lyα absorption lines. We estimate that approximately one-fourth of the extragalactic soft X-ray background (at 0.7 keV) arises from the warm/hot gas, half of it coming from $z < 0.65$, and three-quarters coming from $z < 1.00$, so the source regions should be identifiable on deep optical images.

Subject headings: cosmology: theory — galaxies: formation — large-scale structure of universe — methods: numerical

The cosmic web



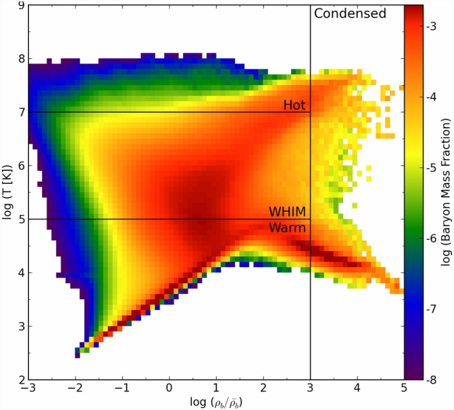
Springel et al. 2005

Filamentary structures observed using weak lensing:
e.g. Clampitt et al. 2016, Epps & Hudson 2017

Warm-hot intergalactic medium (WHIM)

WHIM is diffuse, ionised gas:

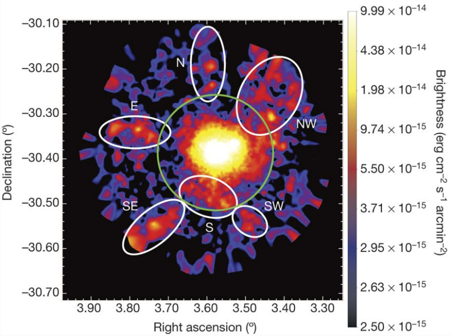
- Low density: = 10
- Temperature: 10^5 10^7 K



Shull et al. 2012

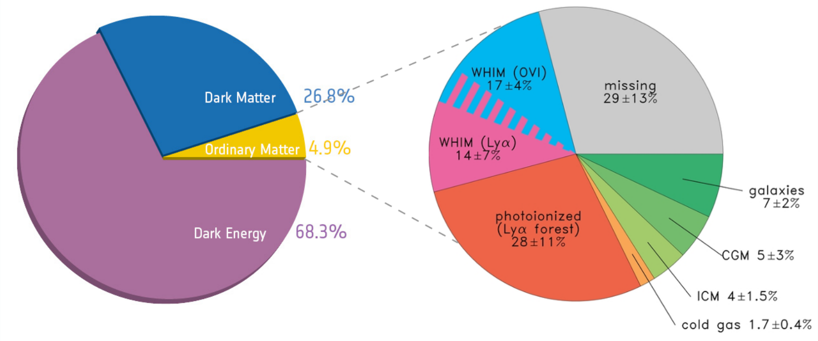
Detecting the WHIM

- Can measure (weak) absorption lines along line-of-sight to quasars
  - ! spatial extent unclear; limited sample size
- X-ray observations are possible in special cases



Eckert et al. 2015, R , — e •

Low redshift baryon census

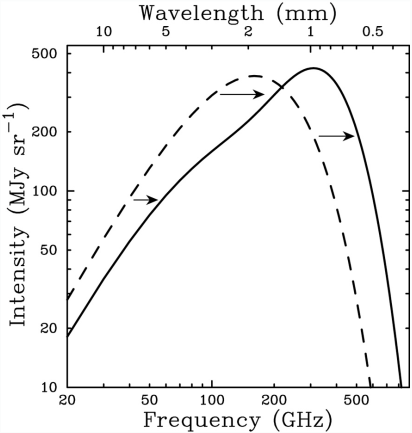


ESA/Planck; Shull et al. 2012

Detecting the WHIM

! Indirect detection of ionised gas possible through the thermal Sunyaev-Zel'dovich (SZ) effect

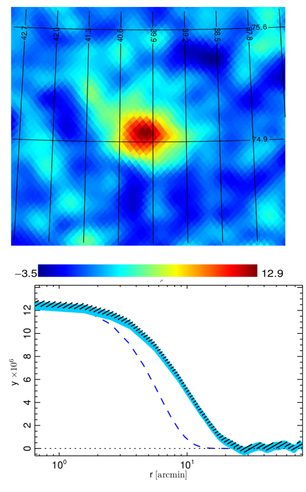
! Spectral distortion / gas pressure:
$Á / \int \; {}_2 ó_2 l$

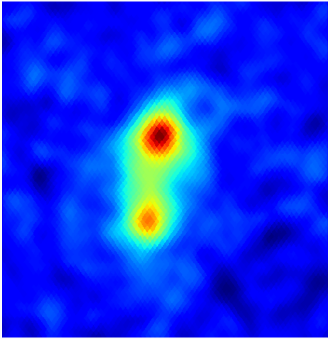


Carlstrom et al. 2002

Observing the SZ effect

SZ effect has been used to detect 10^3 clusters (Planck, SPT)





A399-A401

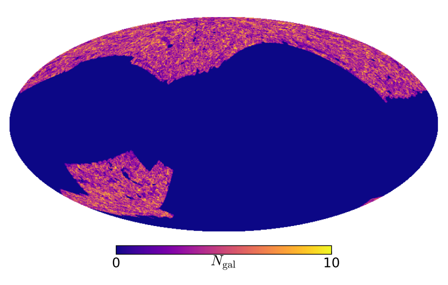
Planck Collaboration 2015 Results XXII (adapted)

Search for gas filaments

! Select pairs of CMASS galaxies

- transverse separation
  6 14 Mpc= Û
- line-of-sight separation
  5 Mpc= Û

! 1 million pairs



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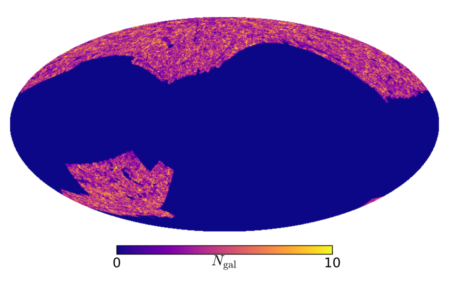
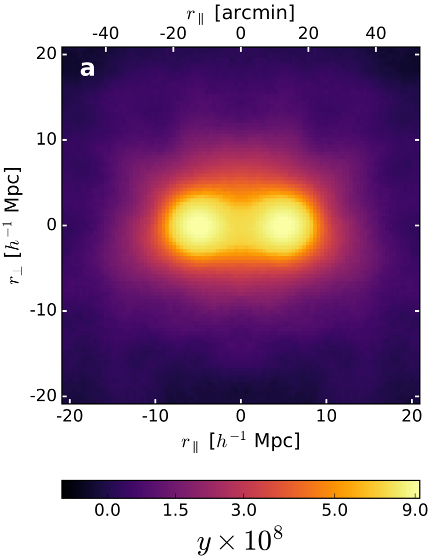


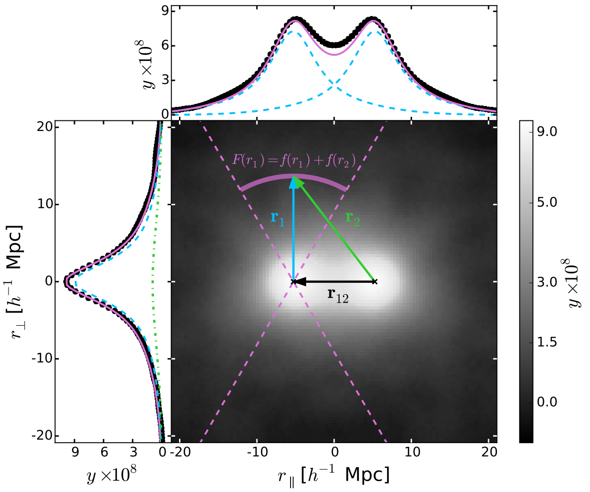
! Stack their SZ signal
(Ámap from Planck 2015 XXII)

SZ stacking result



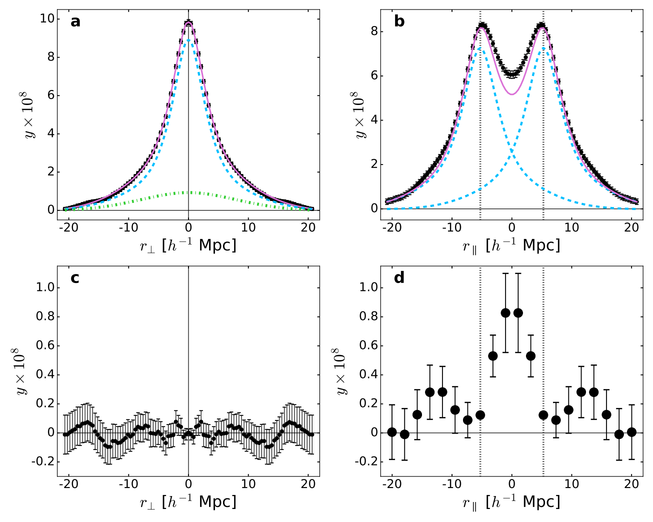
Excess signal?

! Filament or overlapping haloes?



1D profiles

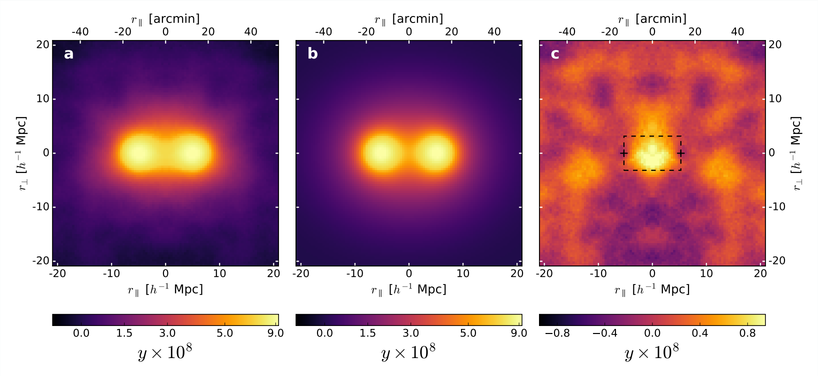
Vertical profile | Horizontal profile



Vertical residual | Horizontal residual

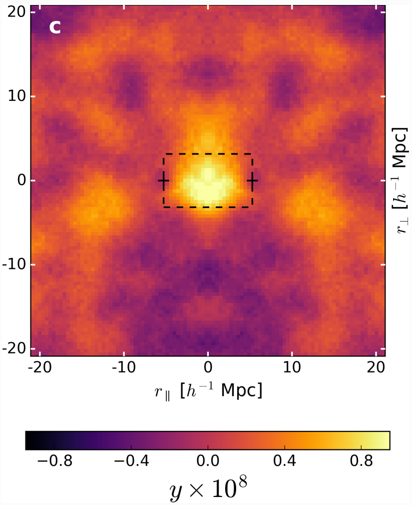
2D result

data | model | residual



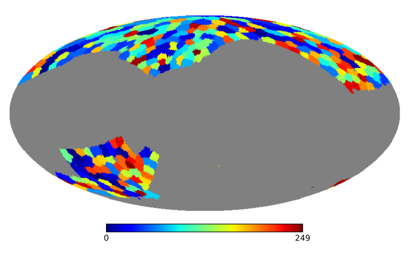
Some questions...

- Is it significant?
- Projection effects?
- Contamination from other astrophysical sources?
- How do we know this is the WHIM?

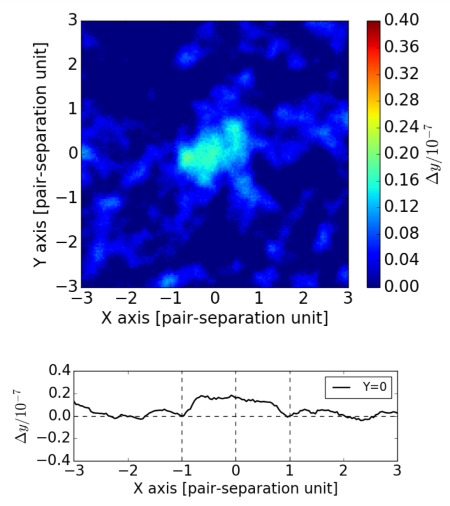


Significance estimate

- CMASS area covers
  9000 deg^2
- 1 million pairs, each span
  0:1 deg^2
- Use jackknife resampling of independent areas:
  - 2:9 result
  - Á= (0:6 0:2) 10^{-8}



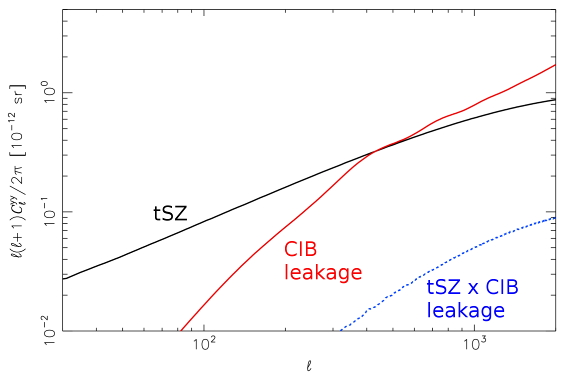
Significance estimate



Tanimura et al. (2017) found
$\acute{A} = (1{:}31 \quad 0{:}25) \quad 10^{8} \; (5{:}3 \quad)$
using $2{:}6 \quad 10^5$ LRG pairs

Contamination I

! Infrared emission from dusty galaxies (CIB) may leak into SZ map

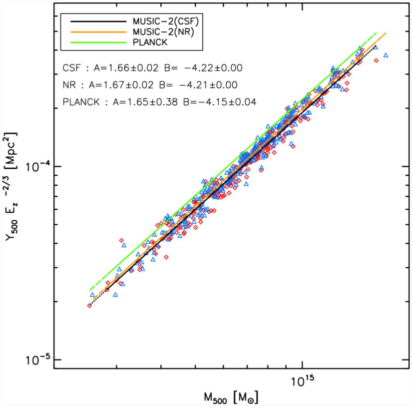


Contributions to the tSZ power spectrum; Planck 2015 Results XXIII

Contamination II

! Diffuse gas from filaments or bound gas in haloes?
Construct simulated Ámap from the Millennium simulation

- Select only the haloes
- Use Y-M relation to assign weight
- Populate haloes with galaxies using HOD recipe
- Repeat stacking analysis for simulated map and galaxy pairs



Sembolini et al. 2013

Contamination II

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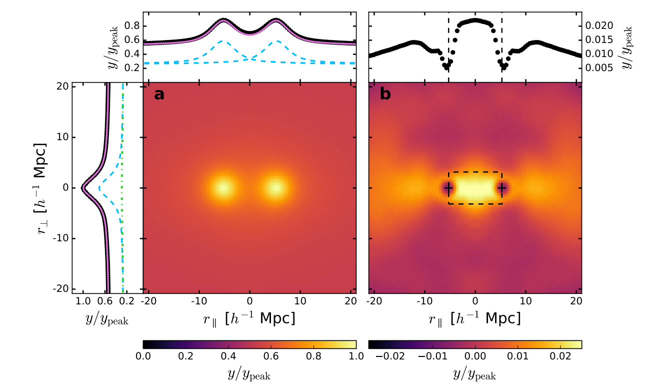
Stack simulated Ámap from the Millennium simulation



! Up to 20% of excess signal may come from bound gas in haloes

Filament properties?

Found large-scale gas filaments (10 Mpc/h), but is it the WHIM?

- Degeneracy problem:
  SZ effect Á/ $_2$ó$_2$

Filament properties?

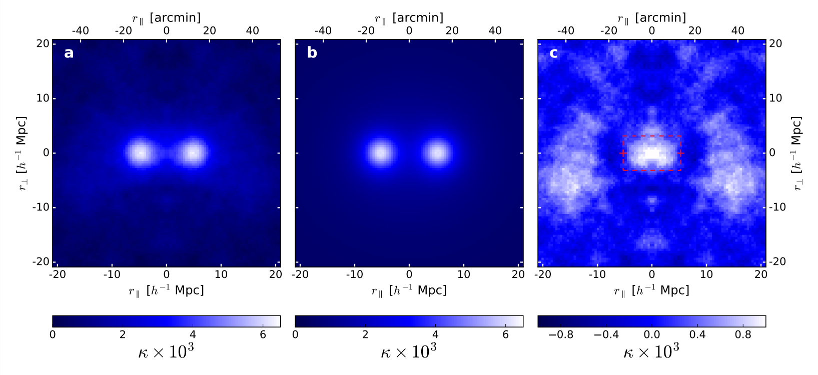
Found large-scale gas filaments (10 Mpc/h), but is it the WHIM?

- Degeneracy problem:
  SZ effect Á/ 2ó2
- Gravitational lensing of CMB by large scale structure can break degeneracy
- Filaments previously detected using CMB lensing by
  He et al. 2018, R,—e• u,e0 0 Á

Planck collaboration/ESA

CMB lensing

data | model | residual

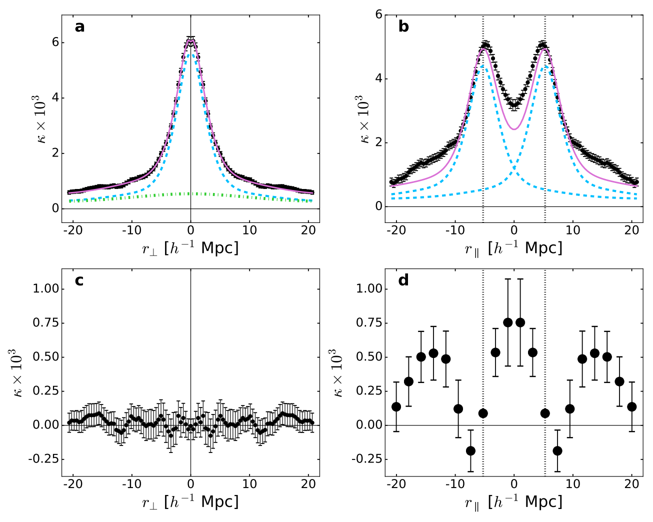


1:9 measurement ! 0:58 10 3

CMB lensing

Vertical profile

Horizontal profile



Vertical residual

Horizontal residual

Filament properties

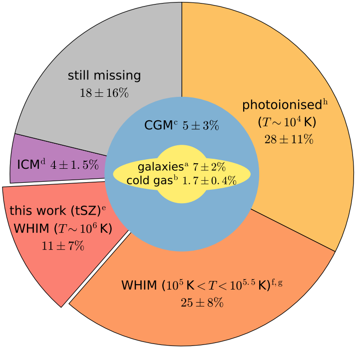
Ą́ are projected quantities ! require assumptions to infer the average filament properties:

- the stacked filament has a cylindrical shape
- matter in the stacked filament follows a Gaussian distribution
- baryons follow the dark matter

Baryon content

- ! Stacking of CMASS galaxy pairs for:
  - CMB lensing gives matter density = (5:5 2:9)
  - the SZ effect (gas pressure) leads to temperature ó= (2:7 1:7) 10^6 K
- ! Accounts for 11% of baryons in the Universe

  Agrees with estimate by Nicastro et al. 2018, R , — e •



Summary & Future work

- Measured the SZ effect and CMB lensing between pairs of massive galaxies
- Bound gas in haloes contributes up to 20% of excess SZ signal
- Filament gas density (6) and temperature (3 10^6K) are consistent with predictions from simulations

- Stacking probes large volume and overcomes cosmic variance but poses other challenges:
  - Room for improvement by varying sample selection and experimenting with different models
  - Weak lensing surveys may help to constrain the filament matter density
  - Future X-ray observations (eROSITA) will help break degeneracy between gas density and temperature